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FIBERIZATION OF SILICATE MELTS IN AN ACOUSTIC FIELD

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A new technology for processing silicate melts into superfine fiber using high-intensity acoustic vibrations is considered. The physical mechanism of liquid dispersion in the presence of an ultrasonic acoustic field is studied. An interpretation of the fiberization process in an ultrasonic acoustic field is provided in the context of capillary-wave and cavitation theories. Results of an industrial test of acoustic-blow technology using specially designed ejection heads are described.

A method and equipment have been developed for industrial processing of silicate melts into superfine fiber using acoustic gas-jet fiber-forming heads (USSR Inv. Certif. No. 827429). Superfine fibers, due to their well-developed surfaces, have increased cohesive capacity, which allows for substantial saving of the binder in the production of articles.

The physical mechanism of the dispersion of a liquid using acoustic vibrations was studied by K. Sollner (1936); however, there are no published data on fiberization in an acoustic-vibration field.

The present paper considers the process of fiber formation in the presence of an acoustic field. In developing the theory of fiberization in an acoustic field, it is expedient to start from the capillary-wave and cavitation hypotheses. The capillary-wave hypothesis consists in minute liquid drops are torn off the crests of standing capillary waves of finite amplitude that are formed on the surface of a dispersed liquid under the effect of an acoustic field. According to the cavitation hypothesis [1, 2], under the effect of acoustic vibrations, a liquid is atomized by impacts arising as a consequence of collapse of cavitation bubbles near the liquid surface.

Let us consider the process of fiber formation from a melt under the effect of external forces with the participation of an acoustic field. Let a melt stream falling vertically from a melting vessel be sucked in by a gas-jet acoustic ejection nozzle and ejected onto a grid conveyer in the form of fiber bundles. Earlier [3] the following relationship was obtained by us from the energy balance equation in analyzing a gas-jet fiber-forming head:

$$l = l_0 \exp\left[\int_0^t \frac{P(t)}{6\eta(t)}\,\mathrm{d}t\right], \tag{1}$$

where l is the fiber length; l_0 is a characteristic dimension of an elementary volume of melt at the initial moment; $P(t)$ is the resultant stress; $\eta(t)$ is the melt viscosity; t is time.

Let us represent the resultant stretching stress $\vec{P}(t)$ in the acoustic field in the following form:

$$\vec{P}(t) = \vec{P}_\mathrm{e}(t) + \vec{P}_\mathrm{a}(t) + \vec{P}_\mathrm{c}(t), \tag{2}$$

where $\vec{P}_\mathrm{e}(t)$, $\vec{P}_\mathrm{a}(t)$, and $\vec{P}_\mathrm{c}(t)$ are, respectively, the specific ejection force, the acoustic pressure, and the acoustic-cavitation pressure.

The case where $\vec{P}_\mathrm{e}(t)$, $\vec{P}_\mathrm{a}(t)$, and $\vec{P}_\mathrm{c}(t)$ are oriented in the same direction is the most favorable for obtaining the maximum stress in fiber stretching. Taking into account expression (2), relationship (1) will take the following form:

$$l = l_0 \exp\left\{\frac{1}{6}\left[\int_0^{\tau_\mathrm{e}} \frac{P_\mathrm{e}(t)}{\eta(t)}\,\mathrm{d}t + \int_0^{\tau_\mathrm{a}} \frac{P_\mathrm{a}(t)}{\eta(t)}\,\mathrm{d}t + \int_0^{\tau_\mathrm{c}} \frac{P_\mathrm{c}(t)}{\eta(t)}\,\mathrm{d}t\right]\right\}, \tag{3}$$

where τ_e, τ_a, and τ_c are, respectively, the duration of action of the ejection force, the acoustic pressure, and the acoustic-cavitation pressure.

Let us consider each of the three components of the resultant stress. If $P_\mathrm{e}(t)$ and $\eta(t)$ vary in accordance with an exponential law, i.e.,

$$P_\mathrm{e}(t) = P_0 \exp(\gamma t);$$

$$\eta(t) = \eta_0 \exp(kt), \tag{4}$$

where P_0 and η_0 are the initial values of the stress and the viscosity, respectively, and k and γ are coefficients, then

$$\int_0^{\tau_\mathrm{e}} \frac{P_\mathrm{e}(t)}{\eta(t)}\,\mathrm{d}t = \frac{P_0\,[\exp(\gamma - k)\tau_\mathrm{e} - 1]}{\eta_0\,[\gamma - k]}.$$

[1] NPF Stroiprogress – Novyi Vek Company, Moscow, Russia; Teploproekt Joint-Stock Company, Moscow, Russia; Moscow Institute of Steel and Alloys, Moscow, Russia.

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If

$$(\gamma - k)\tau_e \ll 1,$$

then

$$\int_0^{\tau_e} \frac{P_e(t)}{\eta(t)}\,dt = \frac{P_0 \tau_e}{\eta_0}.$$

The value of the acoustic pressure P_a is found from the formula

$$P_a = A\rho v\omega \cos\left(t - \frac{x}{v}\right), \tag{5}$$

where A is the shift amplitude; ρ is the medium density; v is the speed of wave propagation in the medium; ω is the circular frequency of the generated waves; x is the present coordinate.

The value of the component

$$\int_0^{\tau_a} \frac{P_a(t)}{\eta(t)}\,dt,$$

related to the acoustic pressure, taking into account expressions (4) and (5), will be equal to:

$$\int_0^{\tau_a} \frac{P_a(t)}{\eta(t)}\,dt = \frac{2A\rho v\omega \sin\frac{\omega\tau_a}{2}}{h_0 e^{k\tau_a}(\omega^2 + k^2)} \times \left[\omega\cos\omega\left(\frac{\tau_a}{2} - \frac{x}{v}\right) + k\sin\omega\left(\frac{\tau_a}{2} - \frac{x}{v}\right)\right].$$

In order to take into account the value contributed by the acoustic-cavitation pressure, it is necessary to know the relationship between the cavitation pressure and the process parameters.

The authors of [4], starting from the Nolting – Nepiras equation, deduced a relationship between the cavitation threshold pressure P_{th} and the viscosity and frequency for a viscous expansion process:

$$P_{th} = P_{at} - P_s + 8\eta f \ln\frac{\overline{R}}{R_0}, \tag{6}$$

where P_{at} is the atmospheric pressure; P_s is the pressure of the saturated liquid vapor; f is the linear frequency; $\overline{R}$ is the "characteristic" radius; R_0 is the initial seed radius.

Whereas acoustic cavitation in water can be excited by an action whose intensity is several watts [5], according to expression (6), the threshold intensity for a silicate melt of working viscosity 1.5 – 2.5 Pa · sec amounts to several kilowatts.

Theoretically, the maximum effect in acoustic cavitation should be observed in the case where the time of vacuum-cavity expansion in a liquid melt and the time of cavity collapse approach the vibration half-period. For a frequency of the generated vibrations equal to 20 kHz, the vibration half-period is equal to 0.25×10^{-4} sec. The duration of cavitation bubble collapse T, according to data in [6], can be found from the expression

$$T = R_{max}\sqrt{\frac{\rho}{P_h}}\,F(\delta), \tag{7}$$

where R_{max} is the maximum seed size; P_h is the hydrostatic pressure; $F(\delta)$ is a certain function of the air content parameter $\delta = P(R_{max})/P_h$, $1 < F(\delta) < 2$; $P(R_{max})$ is the pressure inside the cavity at $R = R_{max}$, which is equal to the sum of the partial pressures of saturated water vapor and air.

According to calculations, the acoustic-pressure amplitude in a silicate melt for the frequencies considered is 2.5 – 5.0 MPa, which makes it possible to take the maximum radius of the cavitation bubble equal to 5 μm [7]. Here the cavity collapse duration according to relationship (7) is around 10^{-4} sec.

On the other hand, the duration of vacuum-cavity collapse in a cooling melt can be estimated using the Frenkel formula in our modification:

$$T = \frac{4\eta_{ef}(R_{max} - R_{min})}{3\sigma_{ef}}, \tag{8}$$

where η_{ef} and σ_{ef} are the effective viscosity and surface tension of the melt; R_{min} is the minimum seed radius.

The effective viscosity and surface tension are understood as certain averaged values of these parameters that take into account their increase under cooling. As $k \to 0$

$$T \to \frac{4\eta_0(R_{max} - R_{min})}{3\sigma_0}. \tag{9}$$

To find the minimum radius of seeds that are capable of causing cavitation, a known cubic equation was used [8]:

$$R_{min}^3 + \frac{2\sigma_{ef}}{P}R_{min}^2 - \frac{32\sigma_{ef}^2}{27P(P - P_a)^2} = 0. \tag{10}$$

The calculated value of the minimum cavity radius was 0.1 μm. For $R_{max} = 5$ μm and $R_{min} = 0.1$ μm, the duration of vacuum-cavity collapse in a liquid melt calculated from relationship (10) yields a value of the order of 10^{-4} sec; taking into account the function related to the air content parameter, this time is somewhat extended.

As a result of processing shock-wave photographs, it was established that in collapse a bubble decreases to 1/20 its maximum diameter, and the pressure inside the bubble is

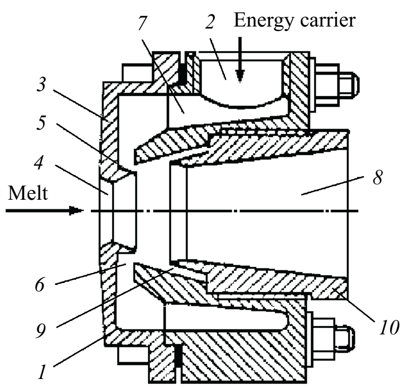

Fig. 1. Scheme of the ejection acoustic head.

equal to 10^3 MPa. Considering this and taking the cavity collapse duration equal to the duration of the cavitation pressure action, one can approximately evaluate the magnitude of the integral that expresses the contribution of cavitation forces to the fiberization.

According to estimated calculations performed on the basis of relationships (6) – (10) and results of studies of W. Gatt (1956), B. Nolting (1950), and I. Nepiras (1951), the specific impulse of cavitation forces can exceed by severalfold the specific impulse of the other forces participating in fiber formation. Accordingly, within the optimum frequency range, the fiberization process in an acoustic field is significantly intensified.

Taking into account conservation of the mass of a melt element and assuming that the initial diameter of a fiber being stretched is equal to half the length of the disturbance wave, it is easy to obtain an approximate relationship for calculation of the fiber diameter using expression (3):

$$d = \frac{\lambda_c}{2\exp\left\{\frac{1}{12}\left[\int_0^{\tau_e}\frac{P_e(t)}{\eta(t)}\,dt + \int_0^{\tau_a}\frac{P_a(t)}{\eta(t)}\,dt + \int_0^{\tau_c}\frac{P_c(t)}{\eta(t)}\,dt\right]\right\}}, \quad (11)$$

where λ_c is the disturbance wavelength.

The known formula for calculation of the disturbance wavelength has the form

$$\lambda_c = 2\sqrt{\frac{\pi\sigma}{\rho f^2}}. \quad (12)$$

Experiments show that it is possible to obtain superfine fibers from various types of melts in an acoustic field, the fiber thickness ranging from fraction of a micron to several microns. This is due to a relatively wide range of sizes of seeds capable of cavitation explosion, different distances between the seed centers and the front surface of the melt stream, the presence of temperature gradients in it, etc.

Acoustic gas-jet heads were tested in production of aluminosilicate fibers and showed positive results. The distribution of fiber diameters was as follows: less than 1 μm – 9%, 1 μm – 13%, 2 μm – 39%, 3 μm – 27%, more than 3 μm – 12%. The fiber diameters agree with calculated values obtained from relationships (11) and (12). At the same time, in a fibrous mixture produced using a standard blow head, the content of fibers whose diameter is over 3 μm exceeded 34%.

It should be noted that acoustic vibrations are manifested not only in the gas-jet method of producing aluminosilicate fiber but also in the centrifugal-roller method, where silica melt is poured from an electric furnace onto a rotating disk and is instantly processed into a fibrous mixture (data of G. Delobel, 1973). The rotating disk is subjected to vibrations whose frequency reaches 8 kHz [9], which presumably produces additional disturbances applied by the vibrating surface to the melt elements.

The cavitation phenomena developed by acoustic vibrations create additional forces in stretching elementary fibers, which increases the fiber length and decreases its diameter. At the same time, certain energy-carrier parameters are significantly decreased. Thus, the heat-carrier pressure is decreased from 1 to 0.25 – 0.45 MPa, and its consumption is decreased from 10 to 6 m^3/min.

The results obtained made it possible to design an acoustic blow head with the calculated parameters (Fig. 1). A design feature of the acoustic ejector consists in an annular resonant cavity in the post-nozzle chamber, whose open side faces the energy-carrier flow (USSR Inv. Certif. No. 827429).

The acoustic blow head consists of: a casing *1* with a connecting pipe *2* for feeding the energy carrier; a lid *3* with an opening *4* for feeding the melt and a connecting pipe *5* that together with the casing forms an ejection nozzle *6*; pre-nozzle chamber *7* and post-nozzle chamber *8*; a resonant cavity *9* that is located between the casing and a sleeve *10* facing the nozzle and is made in the form of a turned ring.

Fiber is produced from a silicate melt in the following way using the ultrasonic method. The energy carrier (steam or compressed air) enters the casing via the input connecting pipe and then is sent via the nozzle at a sonic or ultrasonic speed into the resonant cavity. Ultrasound is generated due to the appearance of self-excited vibrations of the energy carrier jet during cyclic filling of the resonant cavity. The resulting high-intensity vibrations are applied to the rest of the flow.

The acoustic head is equipped with several easily replaceable resonators, each of which can develop acoustic vibrations of a specific frequency and amplitude that are best suited to the flow characteristics of the processed melt.

The head does not require special cooling, since its operation is accompanied by an endothermic effect. The acoustic blow head has several modifications that allow for various supplements to the fiberization process, depending on the technology, namely, feed of fuel, lubricating mixtures, binders, etc. into the blow flame. The resonant cavity, can be arranged in different positions can have different configurations, etc. The efficiency of one ejection head is 150 – 300 kg/h depending on the modification and the blow orientation.

The design of the ejection acoustic head was corrected based on the performed studies. At present, an optimized version of the blow head has been produced that will be used for basalt melt blowing at the Dmitrov Works of Heat-Insulating Products (RF Patent No. 2128149).

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